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Optical properties and thermionic emission in solar cells with InAs quantum dots embedded within GaNAs and GaInNAs

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ABSTRACT

The optical properties of p-i-n solar cells comprised of InAs quantum dots embedded within GaNAs and GaInNAs quantum wells are reported. Strain compensating and mediating GaNAs and GaInNAs layers shift the photoluminescence emission as well as absorption edge of the quantum dots to longer wavelengths. GaNAs and GaInNAs quantum wells contribute also to extending the absorption edge. In addition, the use of GaNAs and GaInNAs layers enhances the thermal escape of electrons from QDs by introducing steps for electrons to the GaAs conduction band.

Quantum nanostructures such as quantum wells (QW) and quantum dots (QD) have drawn interest during last years also for solar cell applications. By changing the QW materials, compositions, and thicknesses, one can optimize the band gap of the solar cell absorber for specific application, whether it is a single junction solar cell or sub-junction in multi-junction device. Different types of QW solar cells have been investigated, including InGaN/GaN, [1] AlGaAs/GaAs, [2] GaNAs/GaAs, [3] and GaAs based GaAsP/GaInAs [4] QWs. A typical problem that needs to be tackle for such multi-layers structure is the compromise between the composition required to ensure a long-wavelength absorption edge and the thickness of the absorber that could be limited by the strain. To this end strain compensation techniques are used for increase the thickness of the absorber to useful level, but at the same time this makes the fabrication more cumbersome. For example, the compressive strain build-up in GaInAs/GaAs QW solar cells is balanced with tensile GaAsP layers resulting in rather complicated structures with even hundreds of interfaces. On the other hand the semiconductor QDs provide alternatives for extending the absorption band in multijunction solar cells, while being more resilient to adverse effect of the strain. Most common examples of such solar cells are based on In(Ga)As [5–7] and Ga(As)Sb [8] QDs, which are fabricated by Stranski–Krastanov (SK) epitaxy, where surface energy is minimized through formation of three-dimensional (3D) islands. However, the SK growth leads to degradation of QD properties and generation of misfit dislocations when the amount of stacked layers is increased [9]. A high level of stacking as well as a high QD sheet density is important because of limited absorption cross section of a single QD layer. Moving towards advanced QD cell concepts, achieving a dense matrix of homogenous QDs is mandatory for intermediate band solar cells. Moreover, the risk of misfit and defect formation increases when the QD density and aspect ratio are pushed to their maximal limits by depositing QDs approaching the threshold of plastic strain relaxation.

Tensile strained layers have been successfully incorporated within stacked InAs QD layers to compensate compressive strain, improving the dot size homogeneity and reducing the strain induced defects [10–15]. Promising results for GaNAs strain compensated InAs QD solar cells, with several QD layers stacked successfully, have been reported [13–15]. Furthermore, one can use strain mediation layers in combination with strain compensation layers, when fabricating stacked QD layers. To this end, a few nanometers thick GaInNAs layers can be inserted in the close proximity of the QDs in order to mediate the highly compressive strain arising from the surrounding semiconductor barriers. Strain mediation layer also forms a QW to the structure. A similar type of strain compensation/mediation has been previously used for the development of dilute nitride GaInNAs/GaNAs/GaAs QWs used in telecommunication laser applications [16]. Besides the strain aspects, when using quantum confined structures one need to pay attention to higher degree of carrier localization that hinders

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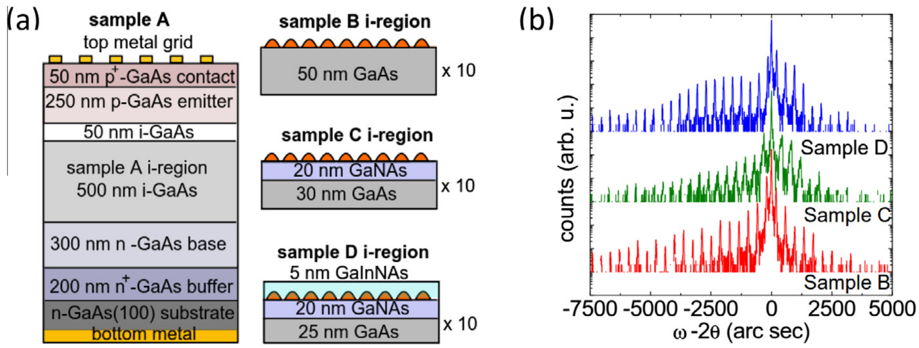

Fig. 1. (a) Schematic sample structure. (b) 2 XRD rocking curves in ω–2θ geometry for samples B–D.

transport and enhances carrier recombination. Facilitating the thermionic escape of carriers should also be considered for increasing the efficiency of the solar energy conversion.

In this paper, we investigate the properties of stacked InAs QD layers with GaNAs and GaInNAs strain compensation and mediation layers. In particular, we report the influence of dilute nitride layers on QDs luminescence properties, spectral response, and thermionic emission of carriers in p-i-n diodes.

Four p-i-n diodes with different intrinsic regions were fabricated on n-GaAs(100) substrate by molecular beam epitaxy (MBE). Sample structures are schematically presented in Fig. 1(a). The intrinsic region of sample A consisted of GaAs. Sample B had ten layers of InAs QDs, formed by deposition of 2 monolayers of InAs, and separated by 50 nm of GaAs. Sample C had 20 nm $GaN_{0.01}As$ strain compensation layers below each layer of QDs to compensate the strain of 2 monolayer of InAs QDs [13–15]. Sample D had an additional 5 nm $GaIn_{0.06}N_{0.01}As$ layer on top of each QD layer. The growth temperature of the intrinsic layers was kept fixed at T_{gr} = 470 °C. After MBE growth, the samples were processed into 4 mm × 4 mm solar cells. We used a Ni/Au back metal contact and a Ti/Au top-grid metal contact evaporated by e-beam through a shadow mask. The composition was analyzed by measuring the X-ray diffraction (XRD) rocking curves in ω–2θ geometry using Philips diffractometer. Room temperature photoluminescence (PL) was measured from each sample using a frequency doubled Nd:YAG laser emitting at 532 nm and an InGaAs detector array (Accent RPM 2000 PL-mapper). The spectral response was measured using a standard lock-in technique while the sample was illuminated with a broadband light source through a DK240 1/4 meter monochromator. The spectral response measurement was calibrated using a NIST-traceable germanium detector.

We should point out that there is a fundamental difference between samples A–D. Although they are here compared to each other, the operation principle as a solar cell is different. Sample A is a normal GaAs solar cell, absorbing photons at higher energy than its band gap. Sample B is a QD solar cell without QW structures. Sample C is strain compensated QD solar cell, with GaNAs strain compensation layer. Sample D, with additional GaInNAs strain mediation layer, is a QW solar cell with embedded QD layers. In such cells, the QW affects strongly to the position of the quasi Fermi level and hence the output voltage of the device.

The compositions of GaNAs and GaInNAs strain compensation and strain mediation layers were estimated by XRD measurements and fit to simulations. First, we defined the N composition from sample C, and used this to define the composition of indium in sample D. The XRD rocking curves are presented in Fig. 1(b). The band anti-crossing model was used for determining the fundamental band-gaps of dilute nitride layers [17]. The composition, band-gaps and lattice mismatch of GaAs, InAs, GaNAs and GaInNAs are summarized in Table 1. Lattice mismatch is determined

Table 1
Compositions, band-gaps, and lattice mismatch for investigated materials.

Material	N-composition	In-composition	Band-gap (eV)	Lattice mismatch on GaAs (%)
GaAs	0.00	0.00	1.424	0.000
InAs	0.00	1.00	0.354	−6.686
GaNAs	0.01	0.00	1.232	0.204
GaInNAs	0.01	0.06	1.191	−0.226

as a difference in the lattice constant $\Delta a = a_{substrate} - a_{material}$ divided by the lattice constant of the substrate. One thing to point out from the XRD data is, that sample C does not have as clear fringes as sample D. Although the fabrication parameters for GaAs/GaNAs and GaNAs/InAs interfaces are the same, sample D appears to have higher interface and/or material quality that could be linked to the use of additional strain mediating layers.

The effect of GaNAs and GaInNAs layers is revealed by the room temperature PL measurements, presented in the left part of the Fig. 2. The QD PL emission shifts to the longer wavelengths when moving from sample A to sample D. Sample A exhibits the GaAs PL peak, while sample B shows PL emission also from InAs wetting layer (WL) at 920 nm and QDs at 990 nm. Strain compensating GaNAs layer in sample C shifts the PL emission of the WL and QD to longer wavelengths by amount of 100 nm, when compared to sample B. Further shift of the QD PL emission, up to 1250 nm, is achieved in sample D where QD layers are capped with GaInNAs. The room temperature PL emission from GaNAs or GaInNAs is not visible in sample D, while in sample C the GaNAs PL emission might overlap with the PL peak of the WL. The drop of the PL intensity for sample C compared to sample B can be related to N-induced defects caused by unoptimized growth condition of GaNAs strain compensation layer, and related nonradiative recombination [18]. However, adding the GaInNAs strain mediation layer (sample D) increases the PL intensity, compared to sample C. When taking into account also the XRD data, it is evident that adding GaInNAs strain mediation layer improves the material quality. Surrounding GaNAs and GaInNAs layers also modifies the confining potential in the QD layer. Energy difference between confined electron and hole states decreases when QDs are surrounded by smaller band gap materials. The interpretation of the PL emission can be compared to a schematic band diagram of the structures revealing the position of the confined QD energy states, which is shown in the right part of the Fig. 2.

The spectral response of the p-i-n diodes, measured within the range of 800–1200 nm, is shown in Fig. 3. The spectral response is reduced at shorter (<900 nm) wavelengths when dilute nitride layers are added to the structure, which is explained by increased N-related defects and decreased amount of GaAs in i-region. When taking into account emitter, intrinsic region, and base, the